

[0001]                    BASE STATION SYNCHRONIZATION  
                         FOR WIRELESS COMMUNICATION SYSTEMS

[0002]                    BACKGROUND

[0003]            The present invention relates generally to digital communication systems. More specifically, the invention relates to a system and method of synchronizing a plurality of base stations in a cellular communication network.

[0004]            The proposed 3<sup>rd</sup> generation wireless protocols require an approach that is based on a simple, but costly procedure of requiring each base station to be externally synchronized to a highly accurate external source.

[0005]            Techniques which support base station synchronization require that a base station passively listen to synchronization transmissions from its neighbors, *e.g.* the synchronization channel (SCH) or the common control physical channel (CCPCH), and follow procedures similar to those performed by user equipment (UE) in order to synchronize. Another approach requires each base station to occasionally send a special synchronization burst in coordination with one or more of its neighbors listening for the transmission. Yet another approach has UEs measure the time difference of arrival of transmissions from each of two cells (TDOA). These techniques utilize a precisely accurate source in every base station. Since each base station has this source, these techniques are costly and inconvenient.

[0006]            Therefore, there exists a need for a system and method that allows fast, efficient, and less expensive synchronization between operational base stations without consuming additional physical resources.

## SUMMARY

[0009] Other objects and advantages of the system and method will become apparent to those skilled in the art after reading the detailed description of the preferred embodiment

## BRIEF DESCRIPTION OF THE DRAWINGS

[0012] Figure 2 is a block diagram of a radio network controller (RNC) made in accordance with a preferred embodiment of the present invention.

[0014] Figure 4 is an illustration of the hierarchal time quality design made in accordance with a preferred embodiment of the present invention.

[0015] Figures 5a and 5b is a flow diagram of the system in accordance with a preferred embodiment of the present invention.

[0017] The preferred embodiments of the present invention will be described with reference to the drawing figures where like numerals represent like elements throughout.

[0018] Figure 1 illustrates a simplified wireless spread spectrum code division multiple access (CDMA) or time division duplex (TDD) communication system 18. The

system 18 comprises a plurality of Node Bs 26, 32, 34, a plurality of RNCs, 36, 38,...40, a plurality of user equipments (UE) 20, 22, 24, and a core network 46. A node B 26 within the system 18 communicates with associated user equipment 20-24 (UE). The node B 26 has a single site controller (SC) 30 associated with either a single base station 30, or multiple base stations  $30_1...30_n$ . Each base station has an associated geographic region known as a cell. It should be known that even though base station synchronization is disclosed, cell synchronization may also be accomplished using the present invention.

[0019] A Group of node Bs 26, 32, 34 is connected to a radio network controller (RNC) 36. The RNCs 36...40 are also connected to the core network 46. For brevity, the following refers to only one node B, but the present invention can be readily applied to multiple node Bs.

[0020] In accordance with a preferred embodiment, the RNC 36 maintains base station synchronization within and between the node Bs 26, 32, 34. Referring to Figure 2, the RNC 36 may request measurements from a base station  $30_1...30_n$  or UE 20, 22, 24 through its message generator 53; receive measurements through its measure receive device 54; optimally update its estimates of states based on these measurements using its synchronization controller 55; and manage a set of states stored in a covariance matrix 57. The stored states are used for synchronization and represent the time error of each base station 30 relative to a reference, the rate of change of each time error, and the transmission delay between base stations 30.

[0021] The RNC 36 also manages a set of measurements stored in a database 59 comprising: time of arrival of a measured waveform (i.e. sync burst); time difference of arrival of transmissions from two base stations as measured by a UE20; and estimates of state uncertainties and measurement uncertainties. The RNC 36 uses advanced filtering, such as Kalman filters, to estimate parameters that define relative clock drift, and to refine parameters such as exact range between one element and another. The estimated time drift is used to infer the frequency mismatch between the frequency references of the respective

base stations and reasonableness checks to ensure that occasional, grossly inaccurate measurements do not corrupt the process.

[0022] The RNC 36 assigns a time quality to each base station  $30_1...30_n$ . This time quality is measured by the RNC 36 by selecting one base station as the time base reference for all others. All other base stations are assigned a variable time quality that is updated based on measurements and applied corrections. The time quality may be an integer (e.g., 0 to 10). A lower quality value implies a better accuracy. Alternately, the quality may be a continuous (floating point) variable. The reference base station (master base station) is preferably, permanently assigned a quality of 0. All other remaining base stations are assigned values which vary and are adjusted with respect to the reference base station. To illustrate this time quality hierarchical design, Figure 4 displays a master base station wherein all base stations slave 1, slave 2, slave 3, are assigned time quality values which vary with respect to the master base station. In one embodiment the time quality of slave 2 base stations are assigned values which vary with respect to the slave 1 base stations and slave 3 base stations are assigned values which vary with respect to slave 2 base stations.

[0023] The normal mode of operation of the RNC 36 updates a covariance matrix 57 for the states stored in the RNC database 59, once per a predetermined time unit (e.g. once per five seconds or a time determined by an operator). One element of the covariance matrix 57 is the estimated variance of each base station's time error.

[0024] When a base station's time error variance exceeds a predetermined threshold, the RNC 36 initiates a message to support that base station's time error update. The update is performed in one of three ways: first, the subject base station is instructed to measure the base station time of arrival (BSTOA) of a sync burst from a neighboring base station  $30_1, 30_2...30_n$ ; second, a neighbor base station  $30_1, 30_2...30_n$  with better quality is instructed to measure BSTOA of the subject base station's transmission; or third, a UE 20 measures the BSTOA of sync bursts of that base stations and a neighboring base station  $30_1, 30_2...30_n$ .

[0025] In the first and second approaches using base station to base station BSTOA, the time of arrival of one base station transmission to another is observed. Referring to Figure 3, a transmitting base station 30<sub>1</sub> sends a known transmission pattern at a predefined time. This transmission pattern may be a sync burst from the sync burst generator 62 of the base station 30<sub>1</sub>, which passes through an isolator 64 prior to being radiated by an antenna 70. The receiving base station 30<sub>1</sub> detects the transmitted waveform using its measurement device 60 which outputs a large value when the received signal coincides with the expected signature. If the receiver and transmitter were at the same location and had precisely synchronized clocks, the output of the measurement device 60 would occur at the same time as the transmitted waveform. However, clock misalignment and transmission path delay causes a time difference.

[0026] Transmission path delay is defined as per Equation 1:

$$R/c + x \quad \text{Equation 1}$$

R/c is the distance, R, between a transmitting unit and receiving unit divided by the speed of light, c. The term x accounts for equipment delays. When base stations are very far apart the quantity, R/c typically dominates. Radio waves travel at the speed of light, approximately 1 foot per nanosecond, or  $3 \times 10^8$  meters per second. The objective of base station synchronization is to align the base stations to within 1-3 microseconds. Therefore, when base stations are separated by distances on the order of ½ mile (1 km) or more, the distances are significant. However, for pico or micro cells, separated by tens of meters, the distances are insignificant compared to the measurement accuracies, x, which dominates.

[0027] Based on these considerations, when attempting to synchronize base stations far apart (more than 1 km) the knowledge of the separation is important. When attempting to synchronize base stations within 50 meters or so, the exact positions become irrelevant. After the measurement of BSTOA is performed, the known propagation distance stored in the RNC database 59 is subtracted and the difference is considered the misalignment in time between the base stations.

[0028] The third approach measures the relative time difference of arrival (TDOA) between two transmissions sent by two different base stations as observed by a UE. The UE measures and reports the observed TDOA between transmissions from two base stations. The RNC 36 sends a message to the UE 20, 22, 24 to measure the TDOA of two base stations. Upon receipt of this message, the UE 20, 22, 24 receives the transmission of the two base stations, via its antenna 72 and isolator 64, and measures the TDOA using the UE measure receive device 68 and transmits the measurements to its associated base station.

[0029] If the UE position is known (*i.e.* its range to each of the two base stations  $r_1$  and  $r_2$  is known) and both base stations timing is correct, the time difference of arrival (TDOA) is defined as per Equation 2.

$$(r_1 - r_2)/c \quad \text{Equation 2}$$

Measured deviations from this value would be an indicator of time base misalignment. As those skilled in the art know, if the ranges  $r_1$  and  $r_2$  are sufficiently small as would be true for pico-sized cells, it would not be necessary to know their values. Observed time difference of arrival could be used directly as a measure of time difference of transmission.

[0030] Once an approach is chosen, the appropriate message is transmitted to either a base station  $30_1 \dots 30_n$  or a UE 22, 24, 20. If the message is sent to a base station  $30_2$ , the base station  $30_2$  is told which neighbor to monitor and measure. If the message is to a UE 22, the UE 22 is told which base station to measure in addition to its own base station.

[0031] Referring back to Figure 2, the RNC 36 has stored the range between each base station  $30_1 \dots 30_n$  within its database 59. It subsequently checks to see if there is a neighbor base station  $30_1$  which has a better time quality than the base station  $30_2$  to be updated. Once such a neighbor base station  $30_1$  is found, a message is initiated to the neighboring base station  $30_1$  to take a measurement from the "out of sync" base station  $30_2$ . Alternatively, the RNC 36 is able to send a message to the "out of sync" base station  $30_2$  and request that it take a measurement of the neighboring base station  $30_1$ . The requested base station, for purposes of this embodiment, the "out of sync" base station  $30_2$ , then takes the

measurement of the "in-sync" base station  $30_1$  and sends the measured value back to the RNC measurement device 54. The RNC measurement device 54 forwards the measured value to the synchronization controller 55 which computes the time of transmission of the measurement by subtracting the propagation time R/C.

[0032] Once the time of transmission is calculated by the RNC synchronization controller 55, the value is compared to the value stored in the RNC database 59. The RNC synchronization controller 55 then computes Kalman filter gains and updates the states in the covariance matrix 57 using the difference between the calculated and predetermined time of arrival and the common gains. If the difference is beyond a certain threshold, the RNC message generator 53 will then send another message to the "out of sync" base station  $30_2$  to adjust its time base or its reference frequency in order to get "in sync" with the other base station  $30_3...30_n$  under the control of the RNC 36.

[0033] The base station  $30_2$  conducts the requested adjustment and reports it back to the RNC measurement device 54. The databases within the RNC 36 is updated, including a correction to the subject base station's  $30_2$  time reference, its time rate of change, an update of its covariance matrix 57 (including, most significantly, its estimated RMS time error and drift error), and an update to its time quality. Referring to Figure 4, a base station whose time base is corrected based on a comparison to another base station, must never be assigned a quality equal to or better than that of a base station to which it is a slave to. This procedure guarantees stability. To illustrate, if a slave 2 base station is to be corrected, the slave 2 base station can only be assigned a value less than that of time quality of its slave 1 base station. This ensures that the time quality of a base station will not synchronize to a slave base station of the same level or less which could eventually lead to a cluster of base stations drifting "out of sync" with the master base station.

[0034] As disclosed earlier, another approach of taking measurements in order to adjust the "out of sync" base station  $30_2$  uses an UE 20, 22, 24. If this method is chosen by the RNC 36, a message is sent to the UE 22 to measure the sync burst of the "out of sync"

base station  $30_2$  and the "in sync" base station  $30_1$ . Once the measurement is taken by the UE 22, the measurements are sent to the RNC 36 and processed. Similar to the methods described above, the measurements are compared to the known measurements stored in the RNC database 56 and covariance matrix 57 and an adjustment measurement sent to the "out of sync" base station  $30_2$ .

[0035] The flow diagram of the system in accordance with the preferred embodiment is illustrated in Figure 5a and 5b. The RNC 36 updates the covariant matrix 57 and database 59 once per unit time (step 501). When the RNC 36 detects that a base station's  $30_2...30_n$  time error variance exceeds a predetermined threshold (step 502), the RNC 36 decides whether to use a base station to measure BSTOA or a UE to measure TDOA in order to update the "out of sync" base station's time error variance (step 503). If the RNC 36 decides to measure BSTOA, a message is sent to a neighboring base station of the "out of sync" base station to measure the base station time of arrival, or the message is sent to the "out of sync" base station to measure the time of arrival of the neighboring base station (step 504). The appropriate base station takes the necessary measurement (step 505) and transmits the measurement to the RNC 36 (step 506). If the RNC 36 decides to measure TDOA, the RNC 36 sends a message to a UE to measure the time difference of arrival of two base stations (step 507a), one being the "out of sync" base station. The UE measures the TDOA of each base station (step 507b) and sends the difference of these measurements to the RNC 36 (step 507c). Upon receipt by the RNC 36 of the appropriate measurements (step 508), the RNC 36 compares the measurement to the value stored in the RNC database 59 (step 509). If the difference is beyond a certain threshold, the RNC 36 sends a message to the "out of sync" base station to adjust its time base or its reference frequency (step 510) in accordance with this difference. The "out of sync" base station conducts the requested adjustment (step 511) and reports it back to the RNC 36 (step 512). The RNC database 59 and covariance matrix 57 are then updated to incorporate the new values (step 513).



[0036] A preferred embodiment is a system and method that resides in each RNC 36. In the prior art, a controlling radio network controller (C-RNC) communicates directly with its base stations and a serving radio network controller (S-RNC) communicates directly with its UEs. For cases where neighboring base stations are under control of different radio network controllers (RNC), there may be a need to add communication between the C-RNCs and S-RNCs that control the neighboring base stations and UEs.

[0037] An alternative embodiment requires each pair of base stations that can hear each other to move its own frequency closer to that of the other. The relative amount of adjustment is defined by a set of unique weights which are assigned to each base station and stored in the RNC database 59. The process of adjusting each of the base stations is the same as disclosed in the preferred embodiment above except that both the "in sync" and "out of sync" base stations are adjusted based on the weights assigned to the respective base stations. With different weights, one can achieve varying degrees of centrality, between the fully central to the fully distributed.

[0038] The most preferred embodiment enables an RNC 36 to send time corrections and/or frequency corrections to a base station  $30_1 \dots 30_n$ . The master base station is responsible to ensure that each of its base stations have a time reference slaved to it, accurate within a specified limit. The RNC 36, in its algorithms and corrections, assumes that there is negligible error existing between the master base station and its base stations and therefore assumes that all base stations have the same time reference.

[0039] As a consequence, the RNC 36 does not attempt to estimate the individual time errors between the master base station and its base stations and the master base station must eliminate or compensate for timing errors between the master base station and each of the other base stations, since the associated RNC 36 does not perform a correction. This embodiment presents a clean interface between an RNC 36 and a master base station. It enables the master base station to apply its own solution to slave synchronization which is well suited to pico-cells.

[0040] In an alternative embodiment, each base station has an independent time and frequency reference which enables an RNC 36 to send time corrections and/or frequency corrections to each base station. The RNC 36, in its algorithms and corrections, estimates the states which represent the time and frequency error of each base station.

[0041] As a consequence, the RNC 36 attempts to estimate the individual time errors between each base station and the master base station, measurements involving one base station provide no benefit to estimating the states of another base station. Therefore, the base station manufacturer need only provide loosely bounded errors in the timing and time drift of the base stations, and every base station must have an acceptable connectivity over the air to another base station (same or different base station).

[0042] This alternative embodiment benefits large cellular areas where the distance between base stations are far. The ability to correct one base station slaved to the time reference of a master base station through measurements involving another base station slaved to the same master base station is limited.

[0043] Each base station in this alternative embodiment uses independent time references but the master base station provides a frequency reference. An RNC 36 sends time corrections for each base station individually and/or a single frequency correction to a master base station. The RNC 36 ensures that the clock of each base station is slaved in frequency to the clock of the master base station. The RNC 36, in its algorithms and corrections, assumes that there is negligible drift error between the master base station and its assigned base stations, but estimates offsets which are treated as constant.

[0044] As a consequence, the RNC 36 estimates the individual time errors between the master base station and its base stations and the common frequency drift of the base stations with regard to the master base station.

[0045] This alternative embodiment has features similar to those described in the previous alternative embodiment where base stations that are far from the master base station benefit. This embodiment provides a mechanism to remove time mismatches in long

distances. Taking advantage of the assumption that these time offsets are stable, this embodiment takes advantage of a measurement involving any base station slaved frequency to the clock of the master base station, to update the drift rate for all base stations slaved to the same master base station.

[0046] Another alternative embodiment has the RNC 36 providing estimates to the master base station to support its synchronization of the base stations slaved to it. An RNC 36 sends time corrections and/or frequency corrections for each associated base station to its respective master base station. The master base station ensures that its associated base stations each have a time reference slaved to itself, accurate within a specified limit. The master base station may elect to use the base station-unique estimates to aid in the base station synchronization. The RNC 36, in its algorithms and corrections, creates a best estimate of the time and frequency error between the master base station and its base stations. In performing state estimates it weighs the relative confidence between the measurements and the base station error uncertainty.

[0047] As a consequence, the RNC 36 attempts to estimate the individual time errors between the master base station and its base stations, and the master base station eliminates and/or compensates for timing errors between the master base station and each base station slaved to its time reference, or requests assistance from the RNC 36.

[0048] While the present invention has been described in terms of the preferred embodiments, other variations which are within the scope of the invention as outlined in the claims below will be apparent to those skilled in the art.

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